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Sensitivity analysis of influencing factors on glass façade breakage in fire

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Abstract

Glass façade is the weakest part of a building. When subject to a fire, its breakage and fallout may create a new vent, allowing the fresh air entrainment and fire spread, which may significantly accelerate the compartment fire development. Previous studies established that a large number of factors can influence the fire performance of glass façades. However, very little is known about the relationship and importance of these factors. In the present work, three different importance analysis methods, including the correlation coefficient, rank correlation coefficient and normalized coefficient of variation, were employed to systematically investigate the primary 16 influencing factors based on experimental and numerical results. The linear relationship, monotony and variation between glass breakage time and these factors are quantitatively analyzed.

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Through comparison of three methods, glass type, fire location and installation form are found to be the three most important factors, while glass thickness, glass dimension and shading width may be ignored during the fire safety design of glass façades. Through the survey from experienced researchers, the thermal shock need more attention as well. The results are intended to provide a reference for fire performance-based design of buildings with glass façades.

Key words: glass façades; breakage behavior; influencing factors; significance analysis

1. Introduction

In recent years, glass façades are increasingly employed in modern high-rise buildings due to their better artistic, durable and environment-friendly characteristics [1]. However, different from concrete and steel, glass is a kind of brittle material that may break and fall out very easily when subject to a big fire. The fallout of glass will create a new vent for fresh air entrance and fire spread outside, facilitating the occurrence of flashover or backdraft. Compartment fire dynamics may thus be considerably changed, causing more serious disasters [2]. In particular, the glass fire resistance plays a very important role in the fire spreading from the interior space to exterior cladding.

This issue was first highlighted by Emmons as "one structural problem of importance to fire growth" [3]. Subsequently, a large amount of work has been conducted [4-11]. It was established that the thermal gradient is the primary cause of glass breakage in the fire, and a large number of factors may influence the fire response of glass [12]. For example, Skelly et al. [7] conducted fire tests within a two-layer fire environment and demonstrated that the edge protection from the frame could significantly shorten the glass breakage time. Manzello et al. [13] and Debuyser et al. [1] determined the performance differences between single-pane and double-pane glazing in a real compartment fire and indicated the importance of glass type selection. By changing the distance between glass and radiation panel, Harada et al. [11] found that the fallout area mainly depends on imposed heat flux. In addition, the smoke movement [4], glass orientation [14], edge condition [8] and fire location [15] were all found to be of great importance to the occurrence of glass breakage.

However, some other parameters do not have as much influence on glass thermal performance as above factors. McArthur et al. [16] compared the performances of timber- and aluminium-framed windows in the fire, but the performances were almost identical under simulated bushfire conditions. Similarly, no significant difference was found between glass frames with or without accessories, such asvinyl film sun screens, bright aluminum or black fiberglass insect screens attached to the exposed side of the window frame [17]. Moreover, experimental results suggested that the restraint of glass almost has no effect on its cracking [11], and the effect of burner-glazing distance change in a certain range can be ignored [18].

A large number of factors whose significances differ markedly will inevitably cause difficulty for the fire safety assessment of glass façades. It is almost impossible to evaluate the glass façades by considering all the factors due to time and expenditure consumption in engineering. In addition, the conflicting data derived from various studies may render the situation more confusing. Previous studies employed Weibull distribution [19, 20], Gaussian distribution [21] or exponential distribution [22] to predict the glass breakage in a statistical method, but primarily focused on the probabilistic characteristic of breakage occurrence and no breakage influence factors were considered. What is more, the previous study objective was limited to the ordinary edge-covered window glass which is anticipated different from glass façades with more diverse characteristics [23]. To the authors' knowledge, no work has been conducted for the analysis of factor significance of glass façades in the fire to date. This ignorance hinders the fire safety design and risk assessment in the construction with a glass envelope [24]. Therefore, it becomes necessary to analyze the significance and relationship between these factors for evaluating of the glass façades response to fire.

In the present study, based on our experimental and numerical results, a total of 16 factors of glass façades, including installation form, wind load, fire location and glass type etc., are analyzed and discussed. The correlation coefficient (CC), rank correlation coefficient (RCC) and normalized coefficient of variation (NCV) methods are employed to calculate the importance of factors to the glass breakage time. What is more, an independent communication and survey from experienced researchers have been conducted. The results are intended to provide valuable references for the development of practical guidelines of glass façade fire safety design.

2. The database and theoretical principles

2.1 The experimental and numerical results

A large number of factors may influence the fire behavior of glazing in a fire. Through systematic experimental and numerical work, 16 primary parameters have been tested in our previous studies [18, 25]. Shading width of the glass frame, temperature increase rate, glass thickness and wind loading of both frame-supported glass (FSG) and point-supported glass (PSG) were tested in a uniform electric radiation apparatus, which can provide a maximum power of 90 kW with a heating dimension of 1.0×1.0 m^2, as shown in Fig. 1(a). The distance between heating source and glass was 500 mm. A thermocouple used to control the radiation apparatus was placed in the cabinet to measure the hot gas temperature. An intelligent temperature-controlled meter was employed to adjust the internal gas temperature increase rate from 5 ºC/min to 25 ºC/min. Then the peak temperature of 600 °C was maintained for 20 min until the glass cracked. A fan was used to simulate the external wind with a maximum speed of 11 m/s. All the glass dimensions were 600×600 mm^2, while its thickness was changed from 4 mm to 19 mm and the shading width was in the range of 10-50 mm. In these tests, the K-type sheathed thermocouples were attached on the glass surfaces by high temperature resistance silver tape and the uncertainties in temperature measurement were estimated to be 5% [20].

On the other hand, the factors, such as burner-glazing distance, glazing type and installation form of both frame and point-supported glazing, were investigated under a 500×500 mm^2 pool fire condition, as shown in Fig. 1(b). N-heptane with 99% purity was used as the fuel. The real fire tests rendered the glass imposed in a much greater thermal shock than that heated by an electric radiation panel. The dimensions of the frame and point-supported glass were respectively 600×600×6 mm^3 and 1200×1200×6 mm^3. The burner-glazing distance was changed from 450 mm to 750 mm, and the glass types included ground, coated, clear, laminated and insulated glazing. For frame-supported glass, the different installation forms included fully exposed, horizontal-hidden and vertical-hidden framing. For point-supported glass, the fixing point position was changed along the horizontal, vertical and diagonal directions. In these tests, the K-type sheet thermocouples were employed to measure the glass surface temperature which were made of aluminum alloy with a high heat conductivity of 226W/m·K. The uncertainty was estimated at 5%. The manufacturer's literature for Gardon type gauges indicates that the accuracy is ±3%, but it will rise to ±8-14% when used in a fire environment [26]. However, it should be noted that only the breakage time, which is recorded by the digital video with 50 frame/sec, is discussed in this present work. For more information about the installation forms, please refer to [27, 28].

Numerical simulations have been performed to investigate the effect of glass dimension, aspect ratio, and fire location on the glass fire performance. Due to the difficulty in strict condition control, these factors are not suitable for experimental investigation. An in-house finite element method (FEM) software was employed for the numerical analysis, as shown in Fig. 1(c). Through comparison with experimental results, it was established that if the temperature loading measured in experiments is implemented, the calculated breakage times agree very well with experimental results and the error can be primarily controlled within 10% [27, 29]. The glass dimension was changed from 100×100×6 mm^3 to 1000×1000×6 mm^3 and the aspect ratio changed from 400:1 to 25:16. What is more, the fire location, represented by high-temperature zone in glazing, moved from edge to the center of the glass pane. The thermal loading was extracted from glass surface temperatures measured in the fire experiments [28].

The time of the first crack occurrence is considered the most important parameter which may markedly affect the compartment fire development [6]. Although some parameters, such as glass surface temperature, incident heat flux, crack path, were obtained, only the time to occurrence of first cracking that represents the fire resistance of glass façades is discussed in this work. Therefore, both the experimental and numerical conditions and the predicted breakage times are summarized in Table 1. Meanwhile, the relevant glass parameters and references in each test and simulation are listed in Table 2. Factors 13-16 have only one data in each case, because no difference exists between numerical calculations when identical boundary condition was applied. For experiments, more repeated data would be helpful for getting more accurate results. Thus, except Factor 7, all the factors were investigated based on several repeated tests. According to the previous data, it was found that in each case, the difference between tests are much smaller than the difference between cases [27, 28]. Moreover, in our tests, all the experimental conditions were controlled strictly. Therefore, it is believed that the results with one or two repeated data may as well provide valuable references. It should be noted that all the data are extracted the from the authors' work [18, 25]. These factors will be analyzed in the following sections in detail.

Table 1. The summary of factors and corresponding time of occurrence of the first crack.

Factor number	Primary factor	Cases	Repeated times in each case	Average breakage time (s)
		Uniform electric radiation condition		
1	Shading width(x_1)	10, 20, 30, 40, 50 (mm)	2	644, 573, 580, 600, 671
2	Temperature increase rate in enclosure air(x_2)	5, 10, 15, 20, 25 (°C/min)	2	1237, 646, 573, 495, 459
3	Glass thickness(x_3)	4, 6, 10, 12, 19 (mm)	2	446, 573, 566, 557, 872
4	Wind load, FSG (x_4)	0, 2, 5, 8, 11 (m/s)	3	626, 602, 575, 552, 488
5	Wind load, PSG(x_5)	0, 2, 5, 8 (m/s)	3	829, 812, 720, 579
		Pool fire condition		
6	Burner-glazing distance, FSG(x_6)	450, 500, 550, 600, 650, 700, 750 (mm)	2	96, 127, 139, 204, 292, 197, --
7	Burner-glazing distance, PSG(x_7)	350, 450, 500, 750 (mm)	1	89, 144, 208, --
8	Glazing type(x_8)	Ground, coated, clear, laminated and insulated glazing	4	91, 164, 214, 332, 366
9	Installation form for FSG(x_9)	Exposed, horizontal-hidden, vertical hidden	3	135, 187, 239
10	Horizontal fixing point position change, PSG(x_{10})	10, 30, 50 (mm) (from point to pane left edge)	3	207, 148, 85
11	Vertical fixing point position change, PSG(x_{11})	10, 30, 50 (mm) (from point to pane upper edge)	3	207, 170, 136
12	Diagonal fixing point position change, PSG(x_{12})	71, 141, 424, 707 (mm) (from point to pane corner)	3	288, 207, 106, 131
		Numerical simulation		
13	Glass dimension(x_{13})	100×100×6, 200×200×6, ...1000×1000 ×6 (mm^3)	1	100, 59, 54, 52, 50, 50, 49, 49, 49, 48
14	Aspect ratio(x_{14})	400, 100, 25, 6.25, 4, 1.5625 (identical area)	1	72, 64, 54, 48, 46, 44
15	Fire location,	200, 400, 600 (mm)	1	44, 40, 38

	FSG(x_{15})	(distance between fire center and pane edge)		
16	Fire location, PSG(x_{16})	200, 400, 600 (mm) (distance between fire center and pane edge)	1	19, 21, 28

Table 2. The glass parameters in each test or simulation.

Factor No.	Dimension (mm^3)	Glass type	Installation form	Thermal loading	Reference
			Uniform electric radiation condition		
1	600×600×6	Single float	FSG	15 °C/min	[18, 30]
2	600×600×6	Single float	FSG	--	[18]
3	600×600×6	Single float	FSG	15 °C/min	[31]
4	600×600×6	Single float	FSG	15 °C/min	[30]
5	600×600×6	Single float	PSG	15 °C/min	[32]
			Pool fire condition		
6	600×600×6	Double float	FSG	Pool fire	[33]
7	1200×1200×6	Single float	PSG	Pool fire	[34]
8	600×600×6	--	FSG	Pool fire	[35, 36]
9	600×600×6	Coated float	--	Pool fire	[27]
10	1200×1200×6	Single float	PSG	Pool fire	[28]
11	1200×1200×6	Single float	PSG	Pool fire	[28]
12	1200×1200×6	Single float	PSG	Pool fire	[28]
			Numerical simulation		
13	--	Single float	FSG	In reference	[37]
14	--	Single float	FSG	In reference	[37]
15	1000×1000×6	Single float	FSG	In reference	[15]
16	1000×1000×6	Single float	PSG	In reference	[15]

2.2 The theoretical principles

Sensitivity analysis is used to evaluate the importance of factors to the outcome in various fields, such as building energy and fire protection engineering [38-40]. There are various sensitivity analysis methods, classified as local sensitivity analysis and global sensitivity analysis methods [41-43]. Local sensitivity analysis method is a partial derivative-based technique, which explores the impact of small input perturbations on the output variable. Global sensitivity analysis methods adopt statistical techniques to analyze the whole impact of input variables in their ranges of variation. Compared with local sensitivity analysis, global sensitivity analysis can assess the importance of each factor to the output in its whole ranges of variation. Global sensitivity analysis involves scatterplots, correlation analysis, regression analysis and variance-based methods and so on [41-45]. Among them, scatterplots can be obtained by plotting data points along the horizontal and vertical axes, which can qualitatively express the relationship between the output and input variables. Correlation analysis contains CC, RCC, partial correlation coefficient (PCC) and partial rank correlation coefficient (PRCC). The CC can analyze the linear correlation between the output and an input variable without removing the effects of the other input variables, which can be used to quantify the strength of the linear relationship between two variables. The formula for calculating the CC between x_i and y denoted by $CC_{x_i y}$ can be written as follow:

$$CC_{x_i y} = \frac{\sum_{j=1}^{n}(x_{ij}-\bar{x}_i)(y_j-\bar{y})}{\left[\sum_{j=1}^{n}(x_{ij}-\bar{x}_i)^2\right]^{1/2}\left[\sum_{j=1}^{n}(y_j-\bar{y})^2\right]^{1/2}} \tag{1}$$

where, n is the number of samples,

$$\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n}(x_{ij}) \text{ and } \bar{y} = \frac{1}{n}\sum_{j=1}^{n} y_j$$

According to the Eq. (1), it can be seen that the value for $CC_{x_i y}$ is between -1 and 1. When the value of $CC_{x_i y}$ is larger than 0, it suggests that the variable y will increase with the increase of x_i, and vice versa. The larger the absolute value of $CC_{x_i y}$ is, and the more significant the linear relationship between x_i and y is. When the values of

$CC_{x_i y}$ are 1 or -1, y and x_i are totally linearly correlated.

On the other hand, the PCC is the CC excluding the linear effects of other variables, which is described in detail in the reference [31]. Besides, The RCC and PRCC can be used to assess the strength of the monotonic relationship between two variables. Firstly, the samples of the variable are ranked by their values. For n samples, the smallest value is set as the rank of 1, the next smallest sample is set as the rank of 2, and the largest value is set as n. Then the CC is applied to the ranks of samples. Thus, the RCC between x_i and y $RCC_{x_i y}$ can be written as Eq. (2):

$$RCC_{x_i y} = \frac{\sum_{j=1}^{n}(R(x_{ij}) - \frac{n+1}{2})(R(y_j) - \frac{n+1}{2})}{\left[\sum_{j=1}^{n}(R(x_{ij}) - \frac{n+1}{2})^2\right]^{1/2}\left[\sum_{j=1}^{n}(R(y_i) - \frac{n+1}{2})^2\right]^{1/2}} \tag{2}$$

where $R(x_{ij})$ is the rank of x_{ij}.

Similar to the PCC, PRCC removes the monotonic effects of the other variables. It can be seen that the values of RCC and PRCC are also between -1 and 1. For negative values of RCC and PRCC, which suggests that output variable will decrease with the increase of input variables. The larger the absolute values of RCC and PRCC are, the more significant the monotonic relationship between y and x_i is. Moreover, the p-value is used to show the confidence level of correlation analysis. Normally, when the p-value is smaller than 0.05, the results of correlation analysis can be used to express the impact of the input on the output variable. The theory of regression analysis is similar to the correlation analysis, which can quantitatively give the linear relationship between the output and input variables based a linear regression model. Regression analysis is characterized in the references [41-43] and is not introduced in the present work.

As mentioned above, if the p-value for correlation analysis is larger than 0.05, it indicates that the results from correlation analysis cannot be used to measure the importance of input variables to the output. The variance-based method is also a typical global sensitivity analysis method, which is used to reflect the importance of input variables through calculating the contribution of the output variance caused by input variables or combinations of input variables [41]. There are main sensitivity index and total sensitivity index for variance-based sensitivity analysis. However, the factors of glass breakage time may be in different ranges, which will lead to different variances of the glass breakage time. The coefficient of variation (CV) of a variable is the ratio of the standard deviation to the mean that is a standardized measure of dispersion of this variable [46]. Moreover, the CV of the glass breakage time is affected by the CV of its input factor. Thus, the idea of the normalized local sensitivity analysis method (i.e., the ratio of the relative variation of the output to the relative variation of the input) [47] is utilized to define a new sensitivity analysis method NCV (normalized coefficient of variation) to remove the effects of the unit and range of factors of glass breakage time to the maximum extent in this paper. The new sensitivity analysis method NCV is based on the CV, which can be written as follows.

$$NCV_{yx_i} = \frac{\left[\sum_{j=1}^{n} (y_j - \overline{y})^2 \right]^{1/2} / \overline{y}}{\left[\sum_{j=1}^{n} (x_{ij} - \overline{x}_i)^2 \right]^{1/2} / \overline{x}_i} \tag{3}$$

From the Eq. (3), it can be seen that the value of the NCV_{yx_i} is larger than 0, and the larger the value of NCV_{yx_i} is, the more important x_i is. Through Eqs. (1), (2) and

(3), It can be found that the precision of CC, RCC and NCV is also associated with the number of the samples, the larger the number of the samples is, the more precise of the outcome of the evaluation.

Our objective is to quantitatively calculate the importance of factors. Thus, the scatterplot method is not adopted in this paper. In addition, the theoretical principles of correlation analysis and the regression analysis are basically similar, which are based on the linear model. The PCC and PRCC are normally used to measure the linear and monotonic strength between two variables with removing the effects of others [47]. The CC and RCC can be used to assess the linear and monotonic strength between two variables with the combined effects of the other variables. In this paper, each factor analyzed in the glass breakage time was studied in a certain specific experimental or numerical simulation condition, i.e., the values of the other factors were almost kept constant, as shown in Tables 1 and 2. It can be obtained that the values of the PCC and PRCC between each factor and glass breakage time are respectively the same as those of the CC and RCC. Thus, PCC and PRCC are not used in this study. Through the above analysis, the CC, RCC and NCV are used here to explore the importance of factors to glass breakage time.

3. Calculated results and discussion

3.1 The calculations of three different methods

For the CC, RCC and NCV quantitative sensitivity analysis methods, numerical values of the input and output are required. However, it is difficult to quantify x_8

(glazing type) and x_9 (installation form for FSG). From Table 1, it can be seen that x_8 contains 5 types of glazing (ground, coated, clear, laminated and insulated), and the corresponding glass breakage times are respectively 91, 164, 214, 332 and 366 s, which increases with the ground, coated, clear, laminated and insulated glazing. Thus, the ground, coated, clear, laminated and insulated glazing are represented by 1, 2, 3, 4 and 5, respectively. Moreover, x_9 includes 3 kinds of installation forms (exposed, horizontal-hidden and vertical-hidden) and the corresponding glass breakage times are respectively 135, 287 and 239 s, which increases with exposed, horizontal-hidden and vertical-hidden installation form for FSG. Then the exposed, horizontal-hidden, vertical-hidden installation form for FSG are respectively set to be 1, 2 and 3. In addition, the factor 13 (glass dimension) is represented by 100 mm, 200 mm, ... to 1000 mm. From the Table 1, it can be seen that the glass breakage time ranges from 19s to 1237s under different conditions. Based on 153 groups of data in Table 1, the Eq.(1), (2) and (3) are respectively applied to factors x_i (i=1,2,…,16) and glass breakage time y to calculate the values of the CC, RCC and NCV. If the absolute values of the CC, RCC and NCV between glass breakage time and its factors is larger, it suggests that this factor is more important. Thus, the order of factors of the glass breakage time can be obtained according to the values of CC, RCC and NCV. The specific value, p-value and order of the sixteen factors are illustrated in Table 3. It should be noted that the p-value is the probability of an observed result assuming that the null hypothesis is true [48]. Thus, in this paper, the p-value is the probability of each factor with glass breakage time being independent. If the p-value of an observed result is small enough, the null hypothesis can be regarded to be rejected according to small probability event principle. The *p*-value can be used to identify whether the null hypothesis (there is no correlation between the factor and the glass breakage time) is correct. Once there is a correlation between two variables identified by *p*-value, the values of CC and RCC can be respectively used to measure the strength of linear and monotonic relationship between each factor and glass breakage time.

Table 3. The summary of importance analysis between glass breakage times and factors.

Factor		CC			RCC			NCV	
		Value	*P*-value	Order	Value	*P*-value	Order	Value	Order
x_1	Shading width	0.3023	0.6211	16	0.4000	0.5046	16	0.1310	14
x_2	Temperature increase rate	-0.8473	0.0700	12	-1.0000	0.0000	1	0.8862	4
x_3	Glass thickness	0.9105	0.0317	10	0.6000	0.2848	15	0.4607	9
x_4	Wind load, FSG	-0.9789	0.0037	6	-1.0000	0.0000	1	0.1091	16
x_5	Wind load, PSG	-0.9724	0.0276	8	-1.000	0.0000	1	0.1669	12
x_6	Burner-glazing distance, FSG	0.8075	0.0520	14	0.8286	0.0416	13	2.4646	1
x_7	Burner-glazing distance, PSG	0.9728	0.1488	7	1.0000	0.0000	1	2.2987	2
x_8	Glazing type	0.9883	0.0015	4	1.0000	0.0000	1	0.9338	3
x_9	Installation form for FSG	1.0000	0.0000	1	1.0000	0.0000	1	0.5561	6
x_{10}	Horizontal fixing point position change, PSG	-0.9998	0.0120	2	-1.0000	0.0000	1	0.6240	5
x_{11}	Vertical	-0.9997	0.0155	3	-1.0000	0.0000	1	0.3115	11

	fixing point position change, PSG								
x_{12}	Diagonal fixing point position change, PSG	-0.8176	0.1824	13	-0.8000	0.2000	14	0.5182	7
x_{13}	Glass dimension	-0.6641	0.0362	15	-0.9847	0.0000	12	0.5127	8
x_{14}	Aspect ratio	0.8886	0.0179	11	1.0000	0.0000	1	0.1165	15
x_{15}	Fire location, FSG	-0.9820	0.1210	5	-1.0000	0.0000	1	0.1502	13
x_{16}	Fire location, PSG	0.9522	0.1976	9	1.0000	0.0000	1	0.4170	10

To describe the results more clearly, the CCs and the corresponding p-values are plotted in Fig. 2. It can be seen that for the parameters x_3, x_4, x_5, x_8, x_9, x_{10}, x_{11}, x_{13} and x_{14}, the p-values of corresponding CCs are smaller than 0.05, which suggests the values of the corresponding CCs can be used to measure the strength of linear relationship between glass breakage time and parameters x_3, x_4, x_5, x_8, x_9, x_{10}, x_{11}, x_{13} and x_{14} [49]. Since the values of the CCs between the glass breakage time and x_3, x_8, x_9 and x_{14} are larger than 0, the glass breakage time displays the linear increase with the increase in x_3, x_8, x_9 and x_{14}. Due to the negative values of CCs between the glass breakage time and x_4, x_5, x_{10}, x_{11} and x_{13}, the glass breakage time will reduce linearly with the increase in x_4, x_5, x_{10}, x_{11} and x_{13}. In order to improve the glass fire resistance performance, we should increase x_3, x_8, x_9 and x_{14} and reduce x_4, x_5, x_{10}, x_{11} and x_{13}. From Fig. 2, it can be seen that the absolute values of the CCs between the glass breakage time and x_3, x_4, x_5, x_8, x_9, x_{10}, x_{11}, x_{14} are larger than 0.9, which suggests these parameters have very significant effects on the glass breakage time. Moreover, the strength of linear relationship between glass breakage time and parameters x_3, x_4, x_5, x_8, x_9, x_{10}, x_{11}, x_{13} and x_{14} is $x_9>x_{10}>x_{11}>x_8>x_4>x_5>x_3>x_{14}>x_{13}$.

The values of the RCCs and corresponding p-values are shown in Fig. 3. For x_2, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{13}, x_{14}, x_{15} and x_{16}, the p-values of the corresponding RCCs are smaller 0.05, which suggests the values of RCCs can be used to measure the strength of monotonic relationship between glass breakage time and x_2, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{13}, x_{14}, x_{15} and x_{16}. From Fig. 3, the glass breakage time will increase monotonically with the increase in x_6, x_7, x_8, x_9, x_{14}, and x_{16} since the values of RCCs are larger than 0. However, the glass breakage time will decrease monotonically with the increase in x_2, x_4, x_5, x_{10}, x_{11}, x_{13} and x_{15} due to the negative values of the RCCs. What is more, the strength of monotonic relationship between glass breakage time and x_2, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{13}, x_{14}, x_{15} and x_{16} is $x_2=x_4=x_5=x_7=x_8=x_9=x_{10}=x_{11}=x_{14}=x_{15}=x_{16}>x_{13}>x_6$, which should be considered prudently for glass fire resistance design.

Furthermore, from the Fig. 2 and Fig. 3 it can be seen that the values of the CCs and PRCCs between the glass breakage time and x_4, x_5, x_8, x_9, x_{10}, x_{11}, x_{14} are similar, whose p-values are smaller than 0.05.

Figure 4 gives NCV for the glass breakage time and factors, which are used to measure the degree of variation of the glass breakage time impacted by the variation of input variables. The values of NCV can be used to compare the importance of factors which may influence glass breakage time. It should be noted that if the value of NCV between the glass breakage time and input parameter is larger, it indicates that this parameter is more important. From Fig. 4, it can be seen that the degree of importance of factors is $x_6>x_7>x_8>x_2>x_{10}>x_9>x_{12}>x_{13}>x_3>x_{16}>x_{11}>x_5>x_{15}>x_1>x_{14}>x_4$. The most important parameters are x_2, x_6, x_7, x_8, x_9, x_{10}, x_{12}, x_{13}, to which more attention should be paid to for glass fire resistance design.

3.2 Comparison and discussion

Three different methods are used to analyze the influencing factors from experimental and numerous results. However, there are some differences between the calculated results which are discussed and compared in this section.

Figure 5 summarizes the importance order of factors of glass breakage time from the CCs, RCCs and NCVs. We divided Fig. 5(a) into three sections: the deep blue, normal blue and light blue represent the significance (orders 1-5) intermediate significance (the orders 6-11) and insignificance (orders 12-16) areas. It can be seen that the degree of importance differs using three different sensitivity analysis methods. The CC and RCC are used to determine the importance of the liner and monotonic relationship. NCV can analyze the importance of dispersion of input variable from the perspective of relative standard deviation. To provide a scientific glass fire safety design, combination of different sensitivity analysis methods may be a good option of identifying the importance of factors of the glass breakage time. Due to no points located in significance area, x_1, x_3, x_{12} and x_{13}, namely shading width (FSG), glass thickness, diagonal fixing point position change (PSG) and glass dimension, are the least important parameters that cannot be predicted linearly. In particular, in the three calculation methods, the order of x_1 (shading width) is always in the range of 14-16, so shading width is suggested to be ignored during glass façade fire safety design. However, x_2, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{14}, x_{15} and x_{16} are the parameters that needed to be paid more attention to. Among them, x_8, x_9 and x_{10}, namely glass type, installation form (FSG) and horizontal fixing point position change (PSG), are found to be the most three important factors because of almost all the points located in the significance area.

To further verify which specific factors are the most important, Figure 5(b) is plotted to demonstrate a clear relationship of calculated results. Only the factors with orders of 1-5 (significance area) are discussed. From the intersections of this diagram, it is established that x_2, x_7, x_8, x_9, x_{10}, x_{11} and x_{15} may be important factors. Among them, the factors of x_9, x_{10} and x_{11} are all related to installation form, and x_7 and x_{15} are both fire location change. The factor x_8 is glass type. Therefore, regardless of FSG or PSG, the fire location, installation form and glass type are the most important aspects in the fire safety assessment of glass façades. For comparison, the averages of orders of the three methods are illustrated in Fig. 5(c). The curve further conforms the significance of x_7, x_8, x_9 and x_{10} (burner-glazing distance FSG, glazing type, installation form FSG, horizontal fixing point position change PSG), and the insignificance of x_1, x_3, x_{12} and x_{13} (shading width, glass thickness, diagonal fixing point position change PSG, glass dimension), which agrees well with the results from the defined area in Fig. 5(a).

Besides the above work, some studies conducted in other conditions can prove the rationality of the analysis results as well. For example, Harada et al. [11] changed the distance between the glass panel and propane burner from 1.5 m to 3 m, the imposed heat flux on glass panel was in the range of 3-10 kW/m^2. The breakage times of float glass without lateral restraint (3 mm thickness) varied from 68 s to 372 s, and some even did not cracked, which indicates the significant influence of burner-glazing distance on glass fire performance. Klassen et al. [5] and Manzello et al. [13] investigated single, double and triple-pane tempered glazing. It was found that despite the fallout of single glazing, the ambient side panel of double or triple-pane glazing can keep intact in a real compartment fire. The reason why these three factors are important is that they change the boundary conditions more significantly than the other factors. For example, installation form changes the mechanical condition, fire location changes the thermal loading and glass type may change the distribution and number of flaws in glazing and the heat transfer process. These change will cause the stress distribution to change considerably which determines the glass breakage occurrence.

From the analysis of the present work and previous studies, the overall suggestion of fire safety assessment of glass façades is shown in Fig. 6. Some factors in Table 1 have been integrated, such as setting fixing position change in horizontal and vertical directions (PSG) and installation form (FSG) as installation form; setting burner-glazing distance (PSG and FSG) and fire location in surface direction (FSG and PSG) as fire location; setting wind load (FSG and PSG) as wind load. Therefore, the factors are simplified regardless of PSG and FSG so as to make the conclusion more applicable. The results are intended to provide valuable references for the glass façade design.

To ensure if the analysis is in congruence with the experience of the researchers, independent communication and survey have been conducted. Six researchers who has experience of glass-in-fire research were asked to fill the questionnaire and give the marks (1 presents the minimum significance and 10 presents the maximum significance) for significance valuations. The average and standard deviation are summarized in Table 4 and the questionnaires marked and signed by interviewees are attached in supplementary documents. It can be seen that the glass type and fire location have the highest scores, followed by installation form, which agree well with statistical analysis. However, different from calculated results, Factor 2, namely thermal shock, may have relatively large significance according to the researchers' experience, thus suggested to be carefully considered during glass design as well.

Table 4. Summary of independent survey from six researchers.

Factor No.	Factors	Average	Standard deviation
1	Shading width	6.5	1.8
2	Temperature increase rate	7.8	1.2
3	Glass thickness	7.3	1.0
4	Wind load, FSG	6.0	1.3
5	Wind load, PSG	6.0	0.9
6	Burner-glazing distance, FSG	8.0	1.3
7	Burner-glazing distance, PSG	7.5	1.2
8	Glazing type	8.7	0.8
9	Installation form for FSG	7.8	1.5
10	Horizontal fixing point position change, PSG	7	1.4
11	Vertical fixing point position change, PSG	7.2	1.2
12	Diagonal fixing point position change, PSG	6.7	1.5
13	Glass dimension	6.8	0.8
14	Aspect ratio	6.3	1.0
15	Fire location, FSG	7.3	1.4
16	Fire location, PSG	7.3	1.4

However, the best way to compare the parameter significances may be to conduct experiments under strictly controlled identical conditions. Considerably more repeated tests should be performed for the statistical analysis in the future, but it is extremely difficult for this kind of work due to the great time and expenditure consumption.

4. Conclusions

The factors of glass façade breakage in a fire have been extensively investigated, but little is known about the significance and relationship of these factors. This work employed three methods, including the correlation coefficient, rank correlation coefficient and normalized coefficient of variation, to calculate the coefficient value, *p*-value and order to compare these influencing factors. A total of 16 factors were analyzed and all the data are extracted from the authors' experimental or numerical studies. The primary conclusions are as follows:

1) The linear relationship between the factors and breakage time is determined by CC analysis. From the value of CC, it is established that the installation form (frame and point supported glazing), glazing type, wind load and glass thickness are the most important linear factors.

2) The monotony is determined by RCC. Except the shading width, temperature increase rate and point position change in diagonal direction, all other factors demonstrate a good positive or negative monotonic relationship with the glass breakage time.

3) From NCV analysis, fire location, temperature increase rate, glazing type are more important than aspect ratio, shading width, wind load from the perspective of the variation of the coefficient of variance concept.

4) Through the comparison of three methods, glass type, fire location and installation

form are found to be the most three important factors, while glass thickness, glass dimension and shading width could be ignored during the fire safety design of glass façades. The thermal shock need more attention as well according to the survey from experienced researchers.

5) The results confirm that the three methods developed for glass breakage analysis are reasonable, and the proposed suggestion may be useful for fire safety design of glass façades. However, to give a robust model, more repeated experiments conducted under identical conditions and systematically statistical analysis are needed for future work.

Acknowledgments

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Figure captions

Fig. 1. Experimental and numerical conditions in our previous work. (a) The setup for uniform radiation panel; (b) Pool fire, frame and point supported glass panels; (c) FEM simulation flow chart and results.

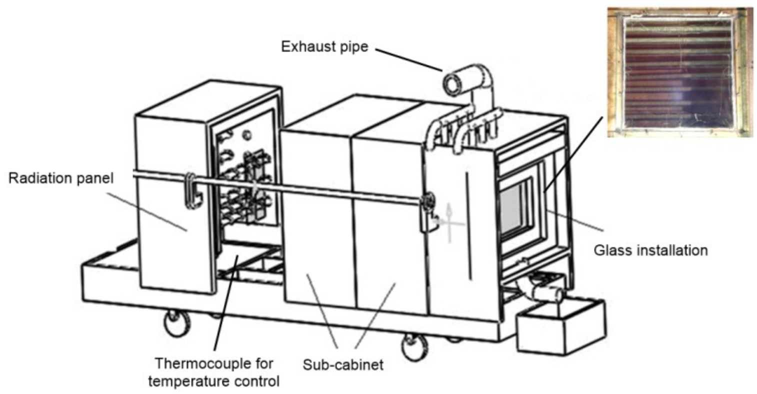
Fig. 2. Correlation coefficient (CC) and corresponding p-value between glass breakage time and factors.

Fig. 3. Rank correlation coefficient (RCC) and p-value between factors and glass breakage time.

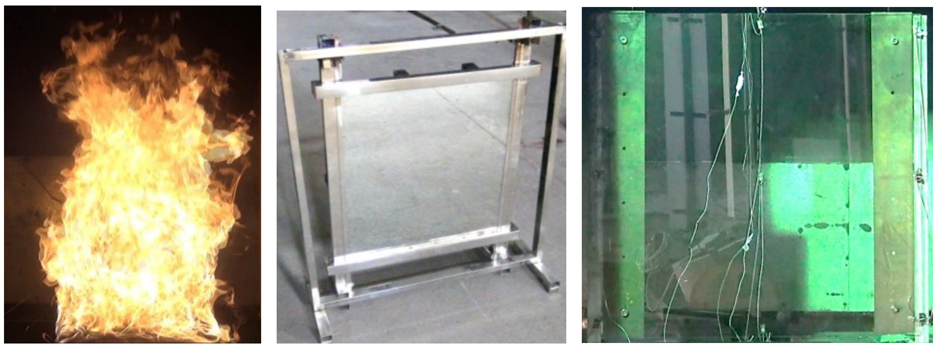
Fig. 4. Normalized coefficient of variation (NCV) between glass breakage time and factors.

Fig. 5. The order of the importance of factors of glass breakage time. (a) Order of importance measures, three areas from the bottom to top are significance intermediate significance and insignificance areas; (b) Relationship of factors in significance area between three calculation methods; (c) Order average of different factors.

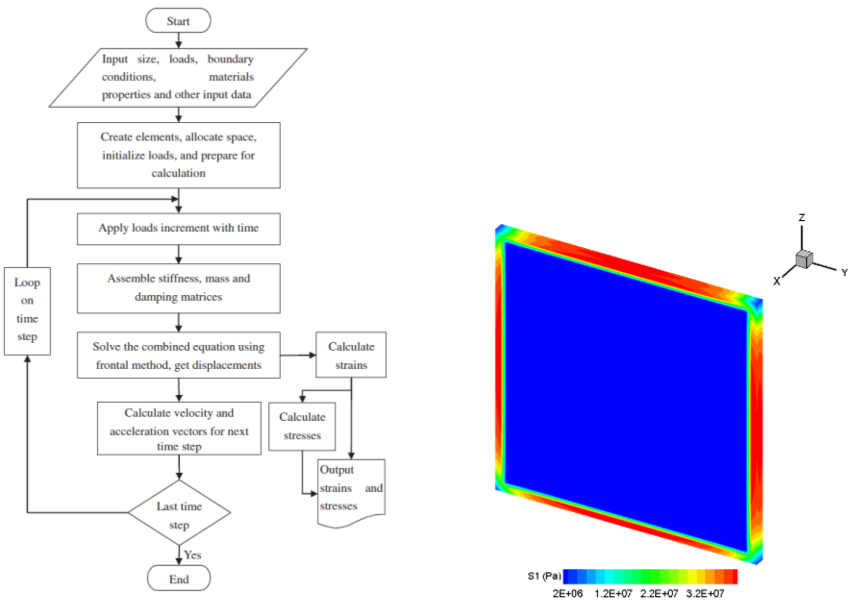
Fig, 6. The order of factor significance for fire safety assessment of glass façades.



(a) The setup for uniform radiation panel



(b) Pool fire, frame and point supported glass panels



(c) FEM simulation flow chart and results

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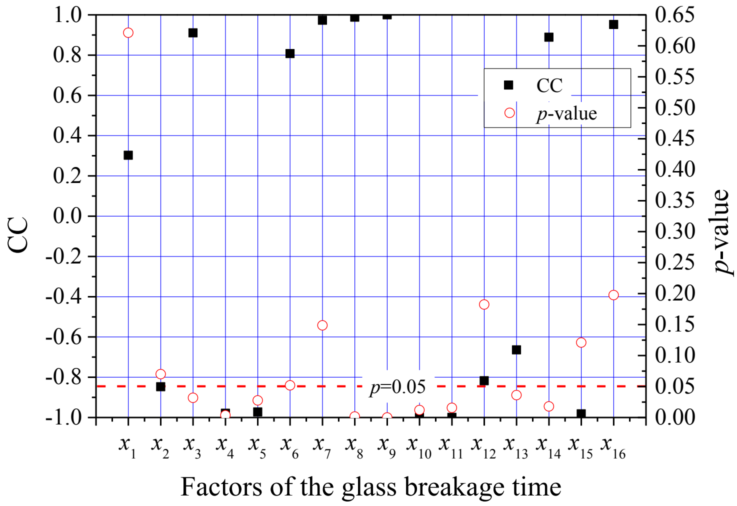
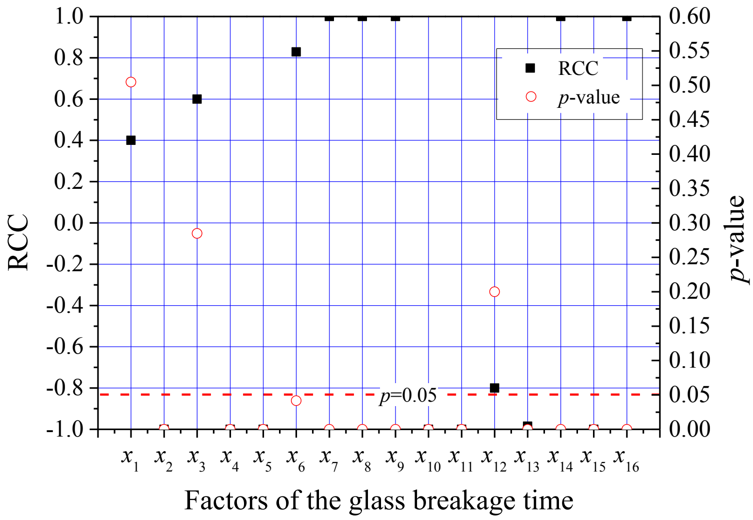


x_1	Shading width	x_5	Wind load, PSG	x_9	Installation form for FSG	x_{13}	Glass dimension
x_2	Temperature increase rate	x_6	Burner-glazing distance, FSG	x_{10}	Horizontal fixing point position change, PSG	x_{14}	Aspect ratio
x_3	Glass thickness	x_7	Burner-glazing distance, PSG	x_{11}	Vertical fixing point position change, PSG	x_{15}	Fire location, FSG
x_4	Wind load, FSG	x_8	Glazing type	x_{12}	Diagonal fixing point position change, PSG	x_{16}	Fire location, PSG

Fig. 2. Correlation coefficient (CC) and corresponding *p*-value between glass breakage time and factors.



x_1	Shading width	x_5	Wind load, PSG	x_9	Installation form for FSG	x_{13}	Glass dimension
x_2	Temperature increase rate	x_6	Burner-glazing distance, FSG	x_{10}	Horizontal fixing point position change, PSG	x_{14}	Aspect ratio
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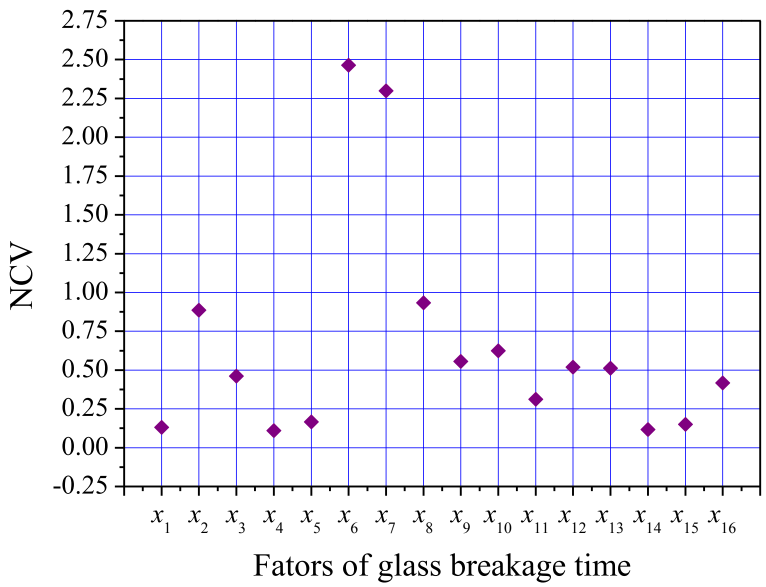
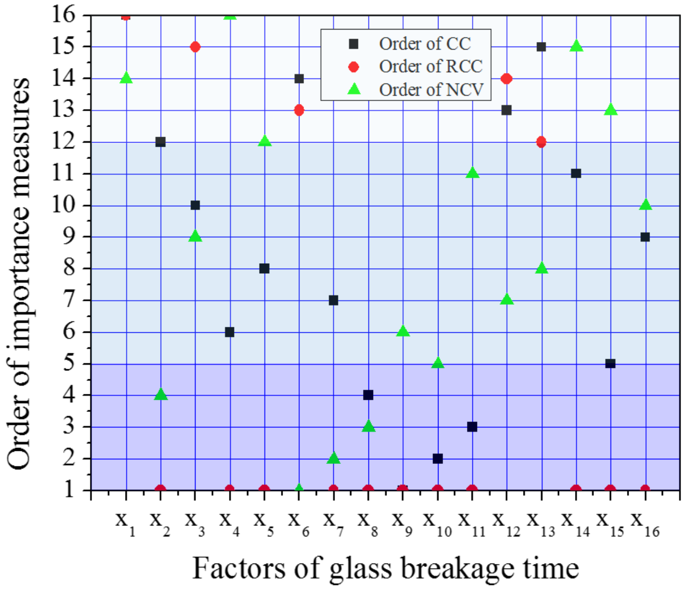
x_4	Wind load, FSG	x_8	Glazing type	x_{12}	Diagonal fixing point position change, PSG	x_{16}	Fire location, PSG

Fig. 3. Rank correlation coefficient (RCC) and p-value between factors and glass breakage time.

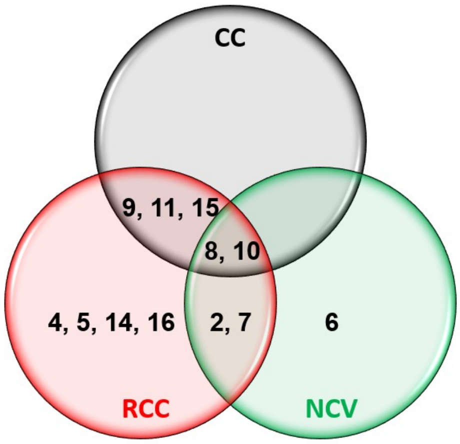


x_1	Shading width	x_5	Wind load, PSG	x_9	Installation form for FSG	x_{13}	Glass dimension
x_2	Temperature increase rate	x_6	Burner-glazing distance, FSG	x_{10}	Horizontal fixing point position change, PSG	x_{14}	Aspect ratio
x_3	Glass thickness	x_7	Burner-glazing distance, PSG	x_{11}	Vertical fixing point position change, PSG	x_{15}	Fire location, FSG
x_4	Wind load, FSG	x_8	Glazing type	x_{12}	Diagonal fixing point position change, PSG	x_{16}	Fire location, PSG

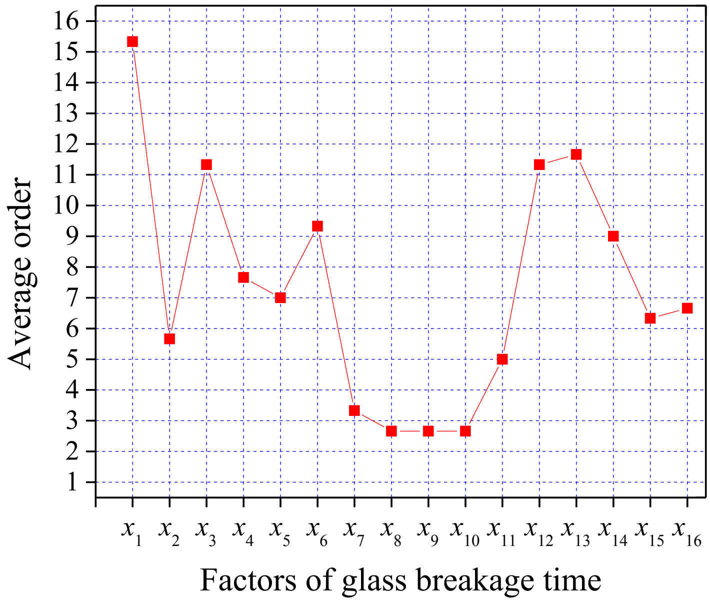
Fig. 4. Normalized coefficient of variation (NCV) between glass breakage time and factors.



(a) Order of importance measures, three areas from the bottom to top are significance intermediate significance and insignificance areas.



(b) Relationship of factors in significance area between three calculation methods



x_1	Shading width	x_5	Wind load, PSG	x_9	Installation form for FSG	x_{13}	Glass dimension
x_2	Temperature increase rate	x_6	Burner-glazing distance, FSG	x_{10}	Horizontal fixing point position change, PSG	x_{14}	Aspect ratio
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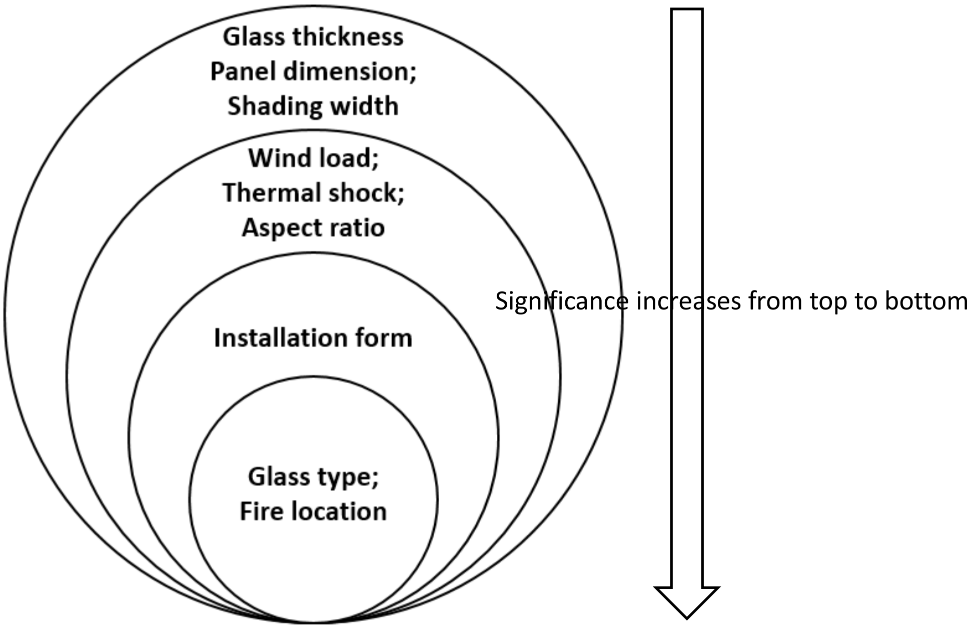
x_4	Wind load, FSG	x_8	Glazing type	x_{12}	Diagonal fixing point position change, PSG	x_{16}	Fire location, PSG

(c) Order average of different factors

Fig. 5. The order of the importance of factors of glass breakage time.



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